Space Cold Chain: From Ground to the International Space Station and Back

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Introduction

Having humans inhabit the International Space Station (ISS) in low earth orbit (LEO), the need to supply goods to the astronauts is vital. Many of the goods supplied to the astronauts require a low temperature for transportation, and some of the experimentation done on the ISS require very low temperatures for safe return to Earth. The Space Cold Chain consists of launching cold items from Earth on a journey to the ISS, then the items are unloaded onto the ISS, followed by repacking and sending cold items safely back to the planet. The main challenge for the Space Cold Chain would be keeping some specific low temperature of the stowage while reducing vibrations and impulses on the products upon launch, delivery, and return.

Given the need for a Space Cold Chain, NASA Johnson Space Center (JSC) created a specialized Cold Stowage Cold Box (technically referred to as a Double Cold Bag or DCB) to keep the items cold for delivery and retrieval from the ISS. The Cold Box needs to perform without an active refrigeration cycle, only passive methods of thermal control would be possible for size and weight constraints. The Cold Box is constructed out of several vacuum panels with aerogel cores. Vacuum panels are fabricated from a hollow metallized plastic shell, and an aerogel core is inserted into the center. The air is then evacuated from the shell to reduce the heat transmission from the outside warmer environment. The outer shell includes a reflective material to reduce radiation heat transfer. These panels are assembled into a rectangular container for cold stowage purposes. This rectangular container dubbed the Cold Box transports cold goods to and from the ISS. Figure 1 presents an example of an assembled Cold Box. The rectangular shape is evident and the reflective coating is visible in Figure 1 (left), however for a flight situation a white, Nomex sleeve is placed over the Cold Box shown in Figure 1 (right).

Figure 1: Assembled Cold Stowage Cold Box without Sleeve (left); Flight-ready Cold Box with Sleeve (right)

To transport cold goods to the ISS, the inner contents of the Cold Box need to be cooled to a specified temperature dependent upon the needs of the transported items. The Cold Box is packed with upper and lower banks of cold bricks to provide passive refrigeration while in transport. Example cold bricks are shown in Figure 2.

Figure 2: Ice Bricks for low temperature application

The cold bricks are an encapsulated phase change material (PCM) for low temperature applications. These cold bricks are placed in a freezer before being implemented into the Cold Box. Freezers reduce the temperatures of the cold bricks to as low as -78°C for cold stowage transportation. For cold products to be sent to the ISS, the bricks are frozen and then placed inside the Cold box in a configuration dependent upon the transported material, and Figure 3 shows examples of the bricks implemented inside the Cold Box. Most configurations the ice brick would line the bottom and top of the Cold Box and the necessary cold items would be packed between the layers with intermittent ice packs as necessary.

The Cold Box in most normal situations contain approximately twenty-four cold bricks (twelve packs at two bricks per pack).

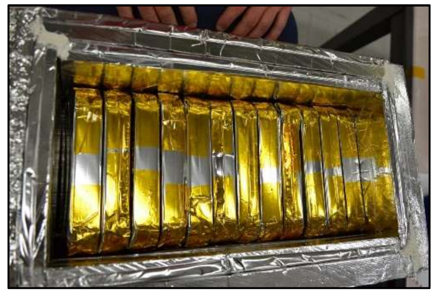


Figure 3: Ice Bricks inside the Cold Box with Transported Goods (left); Ice Bricks Covering the Transported Items (right)

The method of freezing the ice bricks and implementing them into the Cold Box presented the most efficient way to transport goods to the ISS.

The Space Cold Chain is only effective if all the components work; meaning the Cold Box should be able to keep items cold from Earth to the ISS and back to Earth. The main problem faced by the Cold Stowage Cold Box is the return to Earth. The items should be kept at a temperature lower than -68°C. The NASA Kennedy Space Center (KSC) Cryogenics Test Laboratory (CTL) team is tasked with several objectives at the request of NASA/JSC:

1. Keep the contents cooler for a longer duration and provide for return of cold science payloads
2. Maintain a more uniform temperature distribution inside the Space Cooler

Experimental Plan/Procedure

In line with the objectives set by JSC, the team at KSC in the CTL began devising an experimental procedure to test the Cold Box. The Cold Box is similar in concept to any everyday Styrofoam cooler used to keep drinks/food cold or even the more high-performance coolers used for the transportation of temperature sensitive medical items. Therefore the JSC Cold Box was dubbed the Space cooler by the team at the CTL and was compared to commercially available coolers to help work out the new thermal performance test apparatus and methodology. The heat flow rate ("heat leak") for the Space Cooler and the commercially available coolers were experimentally determined via Boiloff Calorimetry [1]. To accomplish the heat leak measurement and thermal performance calculations, a new cold mass device was placed inside the cooler to hold liquid nitrogen (LN2). The complete apparatus (cooler and cold mass device (or LN2 container) was put on a scale to measure the boiloff flow rate from the cold mass device. From the boiloff rate, the heat leak and other thermal performance metrics are be calculated (Figure 4 shows the experimental setup).

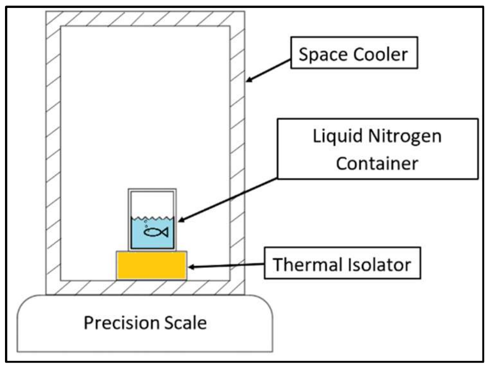


Figure 4: Experimental Setup to Determine the Heat Leak

The Cold Box was tested and compared to the commercially available coolers which were tested in the same orientation. Figure 5 presents the inner contents of the described experimental procedure, and Figure 6 shows the actual test setup on a precision scale and with the sleeve covering. Additional coolers (not pictured here) were also tested in this orientation.

Figure 5: Inside the Space Cooler set up on the scale for initial open-air heat leak

Figure 6: Space Cooler setup on the precision scale for heat leak measurement

Each of the coolers were fitted with thermocouples to capture temperature data on the inside, outside, and in the airspace inside the different containers, and each cooler was placed on precision scales to measure the boiloff rate and ultimately the heat leak rate in joules/second (watts) as a baseline comparison to show how modifications may be able to improve the Cold Stowage Cold Box. The heat leak/Boiloff Calorimetry experimentations are considered a baseline to compare all coolers heat leak rate and to eventually establish a standard thermal performance test for the industry.

Thermal Equalizer

One of the issues with the Space Cooler is the temperature variations inside the cooler created by the ice bricks and the items contained. To negate this adverse effect of thermal variations, a Thermal Equalizer was implemented and tested to counteract the diverse temperature gradients. The Thermal Equalizer was developed by Jean-Pierre Emond and Melissa Germain of Illuminate Consulting LLC (Tampa, FL). This product was created and designed for thermally sensitive products, i.e. medical industry, storage and transportation. The Thermal Equalizer has shown to transfer energy within an enclosed volume to reduce drastic temperature gradients within an enclosure [2].

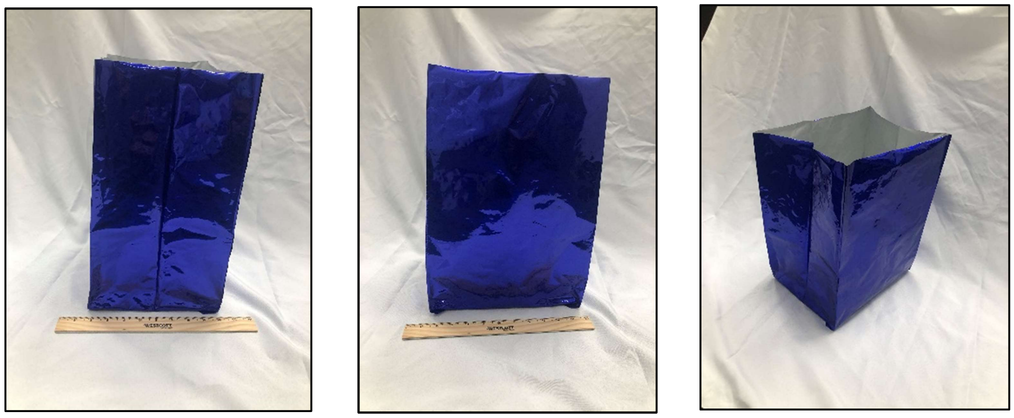
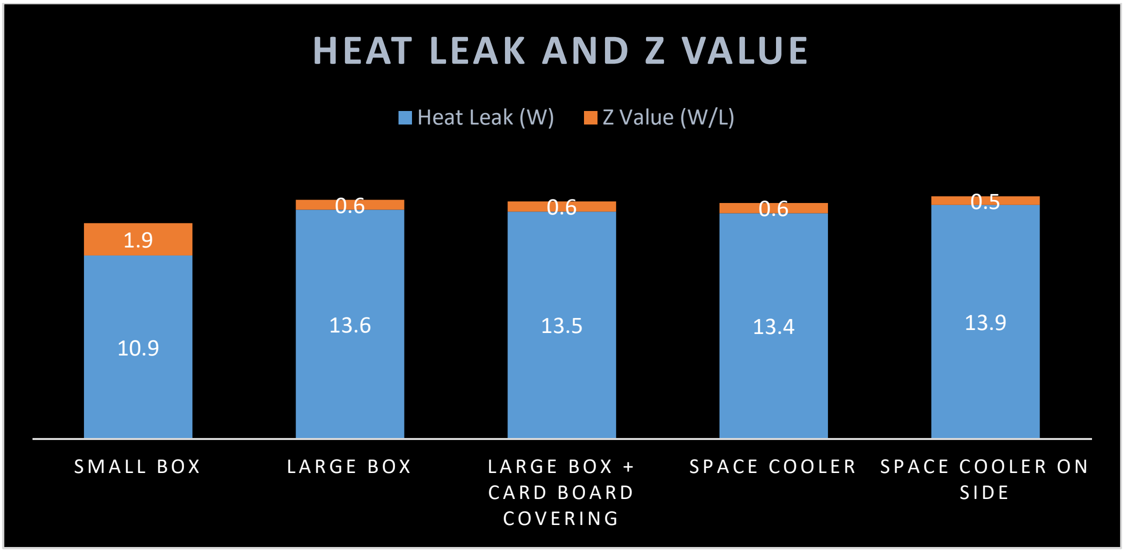


Figure 7: Thermal Equalizer in Different Orientations to Show Details of Design

The Thermal Equalizer was inserted into the Space Cooler with the sleeve and tested in the same manner. Each of the experiments were fitted with thermocouples and compared to the commercially available coolers.

Initial Results

Several types of coolers were tested in the orientation described in earlier sections, and initial results are tabulated for: Small Styrofoam cooler, Large Styrofoam cooler, Space Cooler with sleeve, Space Cooler without sleeve, and Thermal Equalizer inside the Space Cooler. The inner volumes for the Small Styrofoam cooler, Large Styrofoam cooler, and Space Cooler in liters were 6 L, 22 L, and 26 L respectively. Figure 8 show the results for the heat leak experimentation, and the heat leak for each of the cooler is presented in watts (W). The heat flux (W/m2) is also calculated based on the effective heat transfer area (Ae) of the box as defined by ASTM C1774. The effective area for the Small Styrofoam cooler, Large Styrofoam cooler, and Space Cooler in square meters were 0.3 m^2, 0.65 m^2, and 0.75 m^2 respectively. Another term developed is the Z-value (W/L) which is the ratio of heat leak to the inside volume of the container. The Z-value gives a comparative term across all the experiments in order to compare different volume containers.



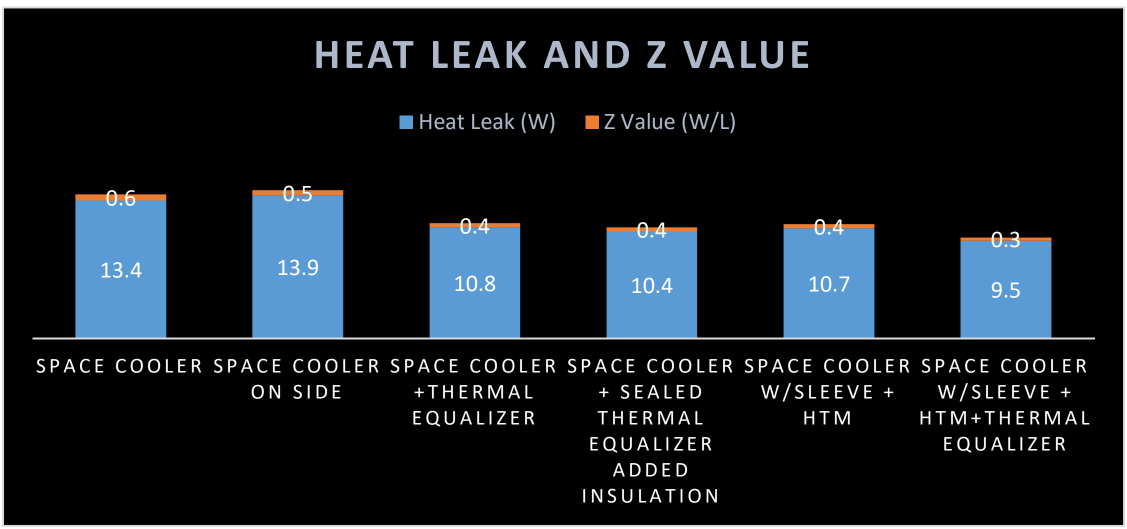


Figure 8: (Top and Bottom) Heat Leak in (W) and the Z-Value in (W/L) for all the experiments

Figure 8 (Top) results show that the small Styrofoam cooler has low heat leak but a very high Z-Value meaning the low volume resulted in lower rate of heat leak. The large Styrofoam cooler, which was of the similar volume as the Space Cooler, had similar heat leak to the Space Cooler of approximately 13 W and identical Z-Values. From Figure 8 (Top) it should be mentioned, the Space Cooler was test sitting upright and on its side to show if orientation would affect the results, and the side orientation showed a higher heat leak rate. Bottom Figure 8 compared the results of the Space Cooler to the results of the Space Cooler with the Thermal Equalizer (TE on graph), and the Thermal Equalizer reduced the heat leak to about 10 W. With the addition of the insulation sealed Thermal Equalizer a percentage difference in heat leak is approximately 25% when compared to the Space Cooler alone. The Space Cooler was tested with and without the sleeve and it shows little change in the addition of the sleeve, however the lowest heat leak rate of 9.5 W was captured in the Space Cooler with the Sleeve and sealed Thermal Equalizer.

Figure 9 presents the temperature data captured inside the Space Cooler at the locations along the wall (upper, middle, and lower) and in the airspace (upper, middle, and lower). The results are presented in temperature differences to show the variation in temperature per location in the Space Cooler with and without the Thermal Equalizer (TE in Figure 9).

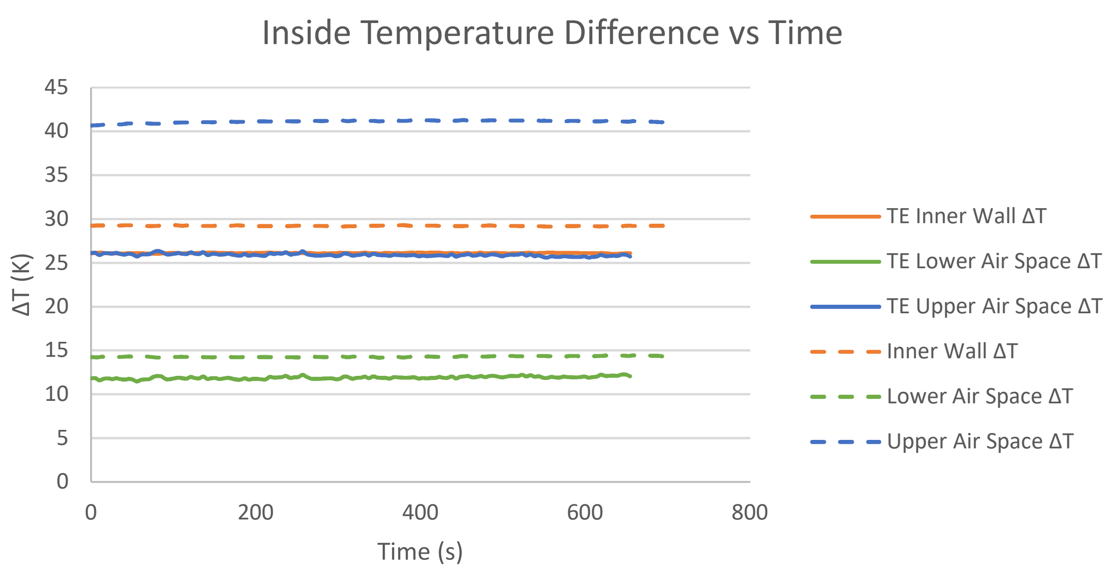


Figure 9: Temperature Difference in the Space Cooler with and without the Thermal Equalizer (TE) as a Function of Time

The solid lines in Figure 9 represent the Space Cooler with the Thermal Equalizer and the dashed lines are the Space Cooler without the Thermal Equalizer. From the figure, the dashed lines are spread out more meaning greater temperature variations inside the Space Cooler without the Thermal Equalizer, however the solid lines are bunched closer together implying the temperature variations were decreased with the implementation of the Thermal Equalizer in the Space Cooler. These initial results show progress in meeting the objectives, but more testing is required. The LN2 boiloff device is undergoing modifications for a final design configuration. When, the final device and procedure are ready, another round of testing of the coolers is needed to confirm the results to date.

Future Experiments

With the promising results presented in earlier sections, more experiments are required of the Space Cooler. Future experimentation is required to meet all criteria set by JSC. After setting a standard thermal performance test the next steps are:

1. Test Space Cooler with 24 cold bricks (12 packs conditioned in a -80°C freezer) in different orientations to simulate real use
2. More in depth experimentation with Space Cooler and Thermal Equalizer insert for comparison
3. Explore operation, design, and materials options to improve thermal performance by decreasing heat leak by 25% or more
4. Correlate time and temperature of the cold bricks test (72+ hours) with the new LN2 boiloff test method

References

[1] Fesmire, J., “Boiloff Calorimetry for Measurement of Very Low Heat Flows, Part 2: Theory of Boiloff Calorimetry, Cold Facts, Cryogenic Society of America, 2016, Vol 32, No 5, pp. 28-29, 34-35

[2] Jean-Pierre Emond, Melissa Germain, “Method and Apparatus for Thermally Protecting and/or Transporting Temperature Sensitive Products.” US Patent 9,689,602 B2, issued June 27, 2017.

[3] Cryogenics Test Lab, NASA, Kennedy Space Center